Present Status of Cavitation Research

by
Robert T. Knapp*

History of Cavitation Investigation

In 1947 the David Taylor Model Basin of the Navy Department published an annotated bibliography of cavitation.(1)** This bibliography contains references to over 800 articles and gives a comprehensive coverage of the literature in this field up to the time of publication. A brief examination suffices to show that this bibliography contains sufficient information to permit the construction of a general outline of the course of the development of work in the field of cavitation. The annotations on the individual items make it possible to classify the articles in a number of interesting ways, some of which can be presented easily by means of histograms.

One of the simplest classifications is that of order of appearance. Fig. 1 is based on the entire group of articles and shows the number of publications appearing each year without regard to the particular aspects of cavitation with which they deal. It is a rather common impression that the hydrodynamic disease of cavitation has been recognized only quite recently. Those having this impression may be somewhat shocked to observe that in 1754 Euler, in his discussion of hydraulic turbines, recognized the possibility of trouble due to cavitation, although he did not call it by that name. However, it will be seen that the 19th century was not very productive, at least as far as number of articles is concerned, since the first one appeared about 1865 and only 18 articles are found in the 35 years that remained in that century. The first 20 years of the 20th century showed a definite increase in interest in cavitation, since 42 articles are listed during this interval. This is an average of slightly over two articles per year, as compared to slightly under one article every two years for the latter part of the 19th century. However, during the first 20 years of this century it will be observed that the average production did not vary appreciably. The big change in interest dates from about 1920, since the following 5-year period averages nine articles per year. The interest grew rapidly, as shown by an average of 24 articles per year for the next 5-year period. For the 5-year period beginning 1930 the average is 36 per year, and for the 1935 period it is 48. This is an all-time high. For the five years beginning with 1940 the number of articles appearing every year dropped to 18. The last three years covered by the bibliography, i.e., 1945, 1946, and 1947, averaged only 12 articles per year. Two factors which tend to explain this great drop in the number of articles on cavitation are (a) the interruption in the normal lines of activity caused by the outbreak of war, and (b) the fact that knowledge concerning some aspects of cavitation was recognized as having military value and therefore not publishable.

---

*Professor of Hydraulic Engineering, California Institute of Technology, Pasadena, California.

**Numbers in parentheses refer to bibliography at end of this paper.

If an examination is made of the country of origin of the publications, it will be found that 80 per cent of them come from three groups: United States, United Kingdom, and Germany plus Switzerland. The number of papers originating in the United Kingdom is about one-half of that originating in either of the other two groups. Fig. 2 shows the histograms for the articles published in these three areas. It will be seen immediately that the United Kingdom showed the greatest activity in the early stages of the work. Indeed, only one article was published in the United States in the last century and that was in 1899. Up to 1920 the United Kingdom had published more articles on cavitation than the other two groups combined. By about 1925-26 each of the three groups had published the same total number of articles, but since that time the United Kingdom, although exhibiting a continuing interest, has been out-produced by the other two groups. In the case of the Germany-Switzerland group the sharp curtailment at the onset of the war is very evident; whereas the other two groups show much less effect.

Two other types of classification have proved interesting: (1) classification according to subject; i.e., the cavitation process, the effects of cavitation on performance, and damage due to cavitation; and (2) classification according to approach, i.e., theory, description, and experiment. In dealing with these classifications the number of listings exceeds considerably the number of articles since many articles contain more than one subject or approach. If totals alone are considered, the following two tables show how the interest is divided with respect to subject and approach.

Table I. Classification According to Subject

	Cavitation Process	Effects of Cavitation on Performance	Cavitation Damage
Totals	211	490	273

Table II. Classification According to Approach

	Theory	Description	Experiments
Totals	252	235	487

If interest is indicated by the number of articles published, two facts stand out immediately from an examination of these totals: first, the interest in the effects of cavitation on performance is equal to the combined interest in the cavitation process itself and in cavitation damage; and second, interest in the experimental approach is equal to the combined interest in theory and description.

Classifying the articles according to subject brings out another fact. Interest in both the cavitation process and in the effects of cavitation on performance developed as soon as the phenomenon was recognized; whereas little or no mention of damage occurs until the beginning of the 20th century.

Mechanics of Cavitation

An attempt will now be made to evaluate the present state of knowledge in several different areas of the cavitation field. This will be followed by a brief discussion of some of the more important problems for future investigation. It should be understood that this material does not purport to be a consensus of the workers now active in the field, but is simply an expression of the current opinion of the author.

It is now generally recognized that cavitation is a dynamic process involving the formation and collapse of vapor-filled cavities in a flowing liquid. With a normal liquid these cavities form in regions where the local pressure drops to vapor pressure and would drop below vapor pressure if the cavity did not form. Conversely, cavity collapse commences when a vapor cavity is transported into a region where the local pressure is above vapor pressure. Studies of a large number of cavitating regions by stroboscopic light and by high speed motion pictures have shown that there are several different types of cavitation which have quite distinctive characteristics. In one very common type a vapor cavity is observed which remains fixed with respect to the boundary surface. Such a cavity fills a region of comparatively constant pressure which closely approaches the vapor pressure of the liquid. Such cavities have the following general characteristics:

(a) The liquid-vapor interface is very active. There is evidence of considerable interchange of material between the two phases, presumably with vaporization in the upstream regions and condensation towards the downstream end. There is physical entrainment from the downstream end of such cavities of vapor or gas by the liquid stream. The character of this entrainment varies with conditions from a smooth, very fine-grained process to a violent, large-scale process in which a major fraction of the cavity may be suddenly swept away immediately followed by a regrowth up to the critical length, at which time entrainment is resumed.

(b) There is a relatively rapid circulation of vapor or gas within the cavity, induced by the interfacial friction with the flowing liquid.

In another distinctive type of cavitation a series of discrete cavities are formed which are not fixed to the solid boundary but travel with the local velocity of the liquid, although their paths may lie extremely close to the solid boundary. In cases in which the pressure distribution in the flow is known for the noncavitating conditions, cavities of this type have been studied in situations in which the total volume of the voids was so small that it could be assumed that their presence had little effect on the pressure distribution. (2) In such cases the cavity is detected at the point in the liquid where the pressure first drops to vapor pressure. The cavity continues to grow as long as the pressure is at or below vapor pressure and starts to collapse as the pressure becomes greater than vapor pressure. Experimental measurements of the time rates of growth and collapse of such isolated spherical cavities agree very well with the behavior that would be predicted from the classical theory of Rayleigh.(3) The deviations that are found to exist appear in the direction that would be expected from the idealized boundary condition used by Rayleigh, e.g., nonviscous, incompressible liquid, completely empty cavity. If this type of cavitation is observed as the intensity is increased, it is seen that the number of cavities per unit area increases rapidly and the state is soon reached where there is obvious interference between them, so that they no longer approximate spheres. During the growth period two or more may coalesce, and in the collapse zone the interaction is so complicated they often collapse in tandem, i.e., the first in a series collapses into the second, etc. Although such distortion and interference make any analysis difficult or impossible, it is quite obvious that the mechanics of the process is the same as that for the solitary traveling spherical void.

Occasionally it is possible, by varying the pressure, velocity, relative size, etc. to obtain two sets of conditions for the same geometrical shape and the same cavitation parameter, where, for one set of conditions the fixed type of cavity is observed, and for the other, the traveling voids. Visual and photographic measurements show that the cavities cover approximately the same relative area on the body. It is estimated that the volume of voids for the two types are comparable. It therefore appears that the end result is about the same in both types of cavitation, i.e., enough cavity volume is created to relieve the tension that would otherwise exist in the liquid in the cavitating regions.

There is another very distinctive type of cavitation that is quite common. This has been observed so frequently at the tips of propeller blades that it is usually called "tip" cavitation. In this type the cavity forms in the core of a vortex. It thus appears as a very long, small diameter tube. On revolving propellers these tubes appear as helices. It should be noted that these cavity tubes trace the path of the propeller tips relative to the liquid and hence do not conform with the flow lines of the liquid.

From time to time what appear to be other types of cavitation have been observed. Usually a little study of their physical characteristics shows that they are made up of a combination of the three types just described.

Effects of Liquid Properties on Cavitation

The previous description of the mechanics of cavitation is typical of cavitation in normal liquids such as water, and in relatively large scale installations such as commercial pumps, turbines, or field structures in general. More detailed examination of the phenomenon has indicated that under some conditions the properties of the liquid may affect the cavitation parameter* at

---

*The cavitation parameter may be defined as $K = \dfrac{p_L - p_c}{\rho \dfrac{V^2}{2}}$ where p_L is the pressure in the undisturbed liquid and p_c is the pressure within the cavity, (usually the vapor pressure corresponding to the liquid temperature), V is the relative velocity, and ρ is the liquid density.

which cavitation first appears (incipient cavitation) and may possibly influence the type of cavitation observed. These liquid properties may be considered in two groups: first, the properties of the pure liquid, and second, the effect of possible impurities on these properties. In considering the properties of the pure liquid, if attention is first given to the method of formation of a bubble or void in a homogeneous liquid, the first property that must be considered is the tensile strength of the liquid. It is commonly assumed that liquids have no tensile strength and yet both theory and experiment agree that pure homogeneous liquids have high tensile strength, of the order of tens of atmospheres or higher. It is obvious that if the tensile strength is effective, it will play an important role in determining the K for incipient cavitation. If in practice the liquid shows little or no tensile strength, the conclusion is that there must be flaws in the liquid, due either to the presence of impurities or to holes in the liquid structure itself. The possibilities of the latter are, of course, determined by the molecular structure of the liquid. Current theories on liquid structure appear to indicate that the probable number of holes per unit volume is far too small to account for the observed cavitation characteristics. This, therefore, tends to focus the attention on the role of the impurities.

The role played by impurities in producing weak spots in liquids has not been completely explored. However, some general remarks can be made. If the impurities consist of completely dissolved gases there is good experimental evidence [4] to show that they have little, if any, effect. For example, water, saturated with air at atmospheric pressure and tested at atmospheric pressure, has exhibited a tensile strength of approximately 500 lbs/sq in when proper precautions have been taken to assure that all of the air present is dissolved and that no trace remains in the gaseous phase. On the other hand, gases present in the liquid in the gaseous phase are obvious flaws in the liquid, since their very presence requires the existence of a gas-liquid interface, and thus reduces the apparent tensile strength of the liquid in the immediate vicinity to zero. If the impurity is a completely miscible liquid it would appear to be comparable to a completely dissolved gas, i.e., it would be expected to be uniformly dispersed throughout the system; there would be no interface and it might be expected to change the effective tensile strength of the liquid only in proportion to its relative concentration and to the difference in its tensile strength from that of the basic liquid. If the impurity is an immiscible liquid the situation is much less clear. If it is dispersed throughout the system, it would be expected to be present in small droplets. Each droplet could be considered as a potential flaw. This weakness would be determined by the interfacial forces as compared with the tensile strength of the pure liquid. If the impurity is a dissolved solid, it could be expected to fall in the same category as a dissolved gas or a miscible liquid and would presumably have little effect on the cavitation properties of the solvent. If the impurity is a solid which is not soluble in the liquid, then each solid-liquid interface is a flaw whose relative weakness depends upon many properties of both the solid and the liquid, such as whether or not the solid is wetted by the liquid, and if so, what is the strength of the bond, the size and shape of the individual solid particles, the surface tension of the liquid, etc. It is difficult to understand how minute gaseous bubbles could exist alone since it would be expected, as the size decreased, that the surface tension forces would become great enough to cause the gas to dissolve completely in the liquid. However, their existence on a solid-liquid or liquid-liquid interface appears possible.

If attention is again turned to the effect of the properties of the pure liquid on cavitation, and if it is assumed that a tiny cavitation void has been started by some means, it is clear that the thermodynamic properties of the liquid (the latent heat, the specific heat, and the heat conductivity), will all affect the rate of growth of this cavity for a given small pressure drop between the inside of the cavity and the surrounding liquid. It should be noted that the growing interest in the roles played by the properties of the liquid and its impurities is not merely an academic one since these factors seem to be the most likely ones to explain both the differences in cavitation behavior shown by different types of liquids, and the "scale effect" that is becoming recognized as existing between cavitation characteristics in geometrically similar flows which differ appreciably in size. This question of scale effect in cavitation phenomena will be considered in somewhat more detail in a later section.

The Effects of Cavitation on Performance

Like many other aspects of this phenomenon, the effects of the presence of cavitation on the performance of hydraulic devices have long been recognized but are still only partially understood. These effects manifest themselves in at least three different ways:

A. An increase in the resistance to flow. For example, in centrifugal and axial flow pumps this effect may appear as an increase in power requirements accompanied by only relatively minor changes in the head and capacity of the unit. In turbines this effect may manifest itself as a drop in power output for a given head and flow rate. One possible explanation of this increase in resistance is that it is the net result of two opposing factors, both of which are concerned with the existence of cavitation voids on or near the guiding surfaces in the cavitation zone. The first factor is a decrease in skin friction on the portion of the surface covered by voids. The second is an increase of form resistance due to the change in effective shape of the surface caused by the presence of the voids. Another way of stating this is that the presence of the voids introduces a new local disturbance which increases the flow loss. Experimental evidence of this balance between two opposing effects is that in some hydraulic machines a slight increase in efficiency has been observed at the inception of cavitation, followed by a drop as cavitation develops. This implies that, in the early stages, the decrease of friction more than balanced the increase in form drag.

B. A major change in or a breakdown of the flow pattern. This effect manifests itself as an upper limit of the flow rate irrespective of an increase in the pressure drop which causes the flow. In a way, this effect may be considered quite similar to the increase in resistance described under A since both are caused by the cavities that form in the flow. However, when the cavity cross section becomes commensurate with that of the remaining liquid stream, the flow velocity may be radically altered both in magnitude and direction.

C. The development of vibration. The "spoiling" of the flow by the presence of cavitation frequently manifests itself in premature separation, the formation of Kármán vortex-streets, and similar pulsating flow phenomena.

If the frequency of pulsation approaches that of the fundamental or a major harmonic of a part of the machine involved, severe vibration may be expected. In extreme cases, powerful low frequency vibrations may be induced that are essentially hydrodynamic in character and do not depend upon resonance with any natural frequency of the machine parts. Here the mechanism may be roughly as follows: Assume that a constant head is available to produce flow in a given circuit whose resistance is so low that if cavitation did not limit it, the flow velocity would be far above that for incipient cavitation. If the flow starts from rest, cavitation will develop as the velocity reaches the incipient cavitation value. As the velocity increases still further, both the degree of cavitation and the circuit resistance coefficient will increase. This latter may progress to such a point that the flow is effectively blocked. With the imposed head remaining constant this may result in an increase in pressure which suppresses the cavitation and thus leaves the flow free to accelerate again until severe cavitation develops once more and the cycle is repeated.

Mechanics of Cavitation Damage

In this phase of the cavitation phenomenon there is a great deal more speculation than knowledge. One of the basic reasons for this state of affairs is that since cavitation damage is caused by the cavitation process, it is extremely difficult to obtain a sound understanding of the mechanics of cavitation damage without first having a sound understanding of the mechanics of the cavitation process itself. Thus it is little wonder that this field is still largely unexplored. However, some landmarks have been charted by the many individuals who have ventured into this area. Some of the principal ones are:

A. Cavitation can damage solids by purely mechanical processes. The evidence of this is of two kinds: 1. Cavitation causes severe damage under conditions in which chemical action is impossible. For example, glass, quartz, or similar inert nonmetallic materials are damaged by cavitation in pure water. Also such corrosion-resistant metals as stainless steel, stellite, gold, platinum, are readily damaged by cavitation in liquids with which they do not react chemically. 2. Several metallographic studies have shown quite clearly that metal surfaces damaged by cavitation also show evidence of mechanical working of the material.

B. In many cases cavitation seems to stimulate corrosion. Experiments have indicated that for a given substance there is a critical intensity of cavitation below which little or no detectable damage takes place. When the cavitation intensity exceeds the threshold value the rate of damage increases suddenly and continues to increase as the cavitation intensity increases. The situation for corrosion is somewhat similar, i.e., a given material may resist the corrosive action of given acids or salts if the concentration remains below the threshold values; whereas if the concentrations are increased above these values, appreciable corrosion damage may result. It has been found, however, that the combined effect of cavitation plus corrosion may produce damage under conditions in which either one acting alone does not. One example of this, which has recently come to the author's attention, concerns the operation of a series of cast iron propellers in sea water. These propellers showed damage only in areas in which cavitation was known to occur. However, such damage was eliminated when a system of cathodic protection was installed. It should be noted that before the cathodic protection was installed there was no damage to the cast iron inthe noncavitating regions, thus showing that corrosion alone could not produce damage to this material. On the other hand, when the cathodic protection was installed damage ceased in the cavitating regions. It is difficult to believe that the cathodic protection affected the intensity of the cavitation; it must be assumed that the cavitation alone was below the damage threshold. Thus, it seems logical to assume that the damage that did occur was the result of the combined effect of the two actions, neither of which alone was severe enough to remove any material. It is the author's opinion that this possibility of combining effects is responsible for much of the confusion which now exists in the literature on cavitation damage.

C. The rate of damage of a solid surface by cavitation is influenced by the surface finish, - the smoother and more flawless the finish the lower the damage rate. Thus, once damage commences it progresses at an accelerating rate, even though the conditions of flow are unchanged. It is obvious that the damage must increase the hydraulic roughness of the surface, but the principal effect on damage rate seems to be an increased focussing or intensification of the shock waves from the collapsing voids.

Relative Resistance of Various Construction Materials to Damage by Cavitation

In this phase of the cavitation field there is a tremendous amount of empirical information. Much of this information consists of direct observations of actual use of various materials under cavitating conditions in hydraulic structures and machines. The material under observation may be either an integral structural part of the equipment, or it may have been applied as a protective overlay. In some cases such protective layers are put on during construction in areas where cavitation is considered most likely to develop. In other cases they are applied to repair cavitation damage. Many publications contain discussions concerning the effect of different methods of application of the protective layer, as well as evaluations of relative resistance to cavitation of different protective materials. There appears to be a general consensus that the best resistance to cavitation damage is exhibited by hard materials with a very high elastic limit and which are not corroded by the liquid used. Examples of such materials are stainless steel and stellite. One material is a very interesting exception to these general rules. In some hydraulic equipment it has been found that a layer of rubber, properly cemented or vulcanized to the metallic surfaces in the critical areas, shows practically no damage under conditions which caused relatively severe damage of the metal surface. However, if the intensity of cavitation is increased above some critical value, the rubber protective layer is destroyed rapidly. Under these conditions the layer has a tendency to come off in large units, and an examination of these pieces shows evidences of high internal temperatures. This behavior is in line with the concept that cavitation damage occurs by mechanical working. Since rubber has a relatively high hysteresis loss and a relatively low heat conductivity, its internal temperature should rise under the effect of cavitation, and if the energy dissipated through hysteresis becomes great enough, its temperature rise could progress to the point at which the rubber would be physically damaged. It is not meant to infer by this that metals could be damaged by high internal temperatures produced by stresses resulting from cavitation, but only to emphasize the mechanical working of the material by the cavitation forces.

A large number of attempts have been made to classify the resistance of materials by means of laboratory tests devised to simulate field conditions. Many such tests have been developed. In this country the one most used is the magnetostriction method. In Europe, in addition to the magnetostriction method, the impingement of a stream or individual drops of the test liquid has been widely used. These tests are reminiscent of the conditions that existed some years ago in the field of strength of materials when many methods were being proposed for measuring the hardness of materials. Attempts were constantly being made to correlate the test results with other physical properties such as tensile strength, wear resistance, etc. Although the different tests were presumably designed to measure the same physical property, the results showed considerable disagreement. Also the attempts to correlate the hardness measurements with other physical properties lead to confusion. It is now apparent that much of the difficulty lay in the fact that there was no clear picture either of the basic nature of hardness or of the factors involved in wear resistance and other physical characteristics of the material with which correlation was attempted. The various laboratory tests to measure the resistance of materials to cavitation damage are showing the same types of difficulty, i.e., the relative resistances found by the different methods do not always agree nor do the results of field use necessarily rank the material in the same order of merit. There are many possible reasons for these discrepancies. There is no conclusive evidence that these laboratory tests actually simulate the conditions causing cavitation damage in field structures and machines. Also it is not certain what are the significant parameters that must be controlled in these tests, as, for example, the surface finish of the material and the intensity of the cavitation. In the author's opinion the latter is a fruitful source of difficulty. For example, the technique commonly used with the magnetostriction test is to establish a given frequency and amplitude of vibration of the specimen in the test liquid and then to observe the damage as measured by loss of weight as a function of time. If the oscillation of the specimen by the magnetostriction tube does produce conditions that are typical of cavitation, they are certainly only of cavitation at one given intensity. As previously stated, there is good evidence to show that different materials have different damage thresholds; however, there is little knowledge concerning the relationship between damage rates and the intensity of cavitation relative to the threshold intensity. Also there is little known concerning the relative behavior of materials having the same damage threshold. Thus, it would seem desirable to be able to make tests of the relative resistance of materials at the cavitation intensities corresponding to that encountered in the application under consideration. However, at this point the investigator following along this path finds himself on the brink of an abyss gazing out over completely unknown territory, since no satisfactory method has been developed for measuring the absolute intensity of cavitation, either in the laboratory or in the field.

Cavitation "Scale Effect"

When a given phenomenon is investigated in the laboratory using relatively small equipment and limited amounts of power, the question usually arises as to how the information obtained can be extrapolated to the larger sizes and higher powers normally encountered in field applications. After a good basic understanding of the mechanics of the phenomenon has been obtained, this question can be answered quite definitely. However, before such a basic understanding has been reached, it may be extremely difficult to obtain satisfactory answers concerning the effects of a change of scale on the phenomenon. Many hydrodynamic phenomena fall under this category, and cavitation is certainly one of them. In the past it has been quite usual to assume that the cavitation parameter, K, offered a satisfactory tool for predicting cavitation performance on geometrically similar devices. The assumption was that tests of geometrically similar objects of different size would all show the same cavitation performance when operating at the same cavitation parameter. Since K involves only pressures and velocities, this is equivalent to assuming that cavitation is independent of size. In the last few years laboratory investigations have indicated that a change in physical size does affect cavitation even within the relatively small variations possible with laboratory equipment. However, in some directions these experiments are not conclusive. There is good evidence to indicate that the properties of the liquid and its undissolved impurities play a significant role in its cavitation performance, but as yet little has been done to control these properties other than to maintain a relatively constant temperature and dissolved gas content.

The evidences of scale effect found in the laboratory have all been in the same direction, i.e., a suppression of cavitation until after the local pressure has dropped measurably below the vapor pressure. Another way of stating this is that an effective tensile strength may be observed under some laboratory conditions. This effective tensile strength appears to increase as either size or velocity decreases. From this type of evidence, the author has tentatively concluded that for a given set of liquid conditions the significant parameters are size and shape of the test body and velocity of flow, since these determine the intensity and duration of the tensile stress to which the liquid is subjected before cavitation begins, and that the depression, ΔK, of the incipient cavitation parameter below the value computed on the basis of zero tensile strength is a measure of their combined effects. It is believed that probably some relationship, $f(v, d, \Delta K) = \text{Const.}$, exists. Such a relationship, if it could be found and verified both experimentally and analytically, would give a direct method of computing scale effect. Attempts to correlate such expressions as $\Delta K\sqrt{vd} = \text{Const.}$, and $\Delta K v\sqrt{d} = \text{Const.}$ with the experimental results have been somewhat encouraging, but the evidence is yet too meager to justify more than passive interest.(5) (6)

Needs for Future Work

It is always dangerous for a person to attempt to peer into the future and to make predictions as to what will take place. The author intends to make no such attempt with regard to cavitation, but will content himself with a brief discussion of what he believes are some of the urgent needs for additional information.

In the author's opinion, the most important immediate need is for more detailed study of the mechanics of cavitation, in particular as it applies to the "fixed" type cavity and to moving cavities so closely spaced as to cause mutual interaction. Such a study is inherently involved with the physical properties of liquids and of the normal impurities that they contain so that, for all practical purposes, an investigation of the properties of the liquid system can be considered a part of the detailed study of the mechanics of cavitation.

Next in point of need would fall the investigation of the mechanics of cavitation damage. This does not necessarily mean that it is second in importance, but simply reflects the fact that progress in many parts of this field must wait until more knowledge has been obtained about the mechanics of the cavitation process.

It is believed that the most serious lacks in our knowledge of the effects of cavitation on performance are first, a quantitative understanding of the mechanics of the increased resistance to flow produced by cavitation, and second, the location and extent of various types of cavitation which occur in hydraulic machines, and the effects of changes in operating conditions on these quantities.

Future work in the determination of the relative resistance of materials to cavitation damage should be guided by the knowledge that becomes available concerning the mechanics of the cavitation damage. It would appear that one fruitful field for investigation would be the development of an acceptable definition of intensity of cavitation and of some rational measure of it which could be used both in actual hydraulic machines and structures and in the laboratory equipment employed for determining relative resistance.

In the determination of scale effect for cavitation model studies, it is believed that more carefully controlled experiments would be valuable, because at the present time the amount of experimental information available is too meager and too limited in scope even to outline the field. It must be remembered that in this field it is necessary that scrupulous attention be given to secure exact geometric similarity if valid results are to be obtained. It is anticipated that the analysis of the significance of the results in this field will be greatly assisted by the progress that will undoubtedly be made in the understanding of the mechanics of cavitation.

Bibliography

(1) Raven, F.A., Feiler, A.M., and Jesperson, Anna. "An Annotated Bibliography of Cavitation". U. S. Navy Department, David Taylor Model Basin, Report R-81. December 1947. 204 pp.

(2) Knapp, Robert T. and Hollander, A. "Laboratory Investigations of the Mechanism of Cavitation". Trans. ASME. vol. 70, 1948, p. 419.

(3) Rayleigh, Lord. "On the Pressure Developed in a Liquid During the Collapse of a Spherical Cavity". Phil. Mag. vol. 34, 1917, p. 94.

(4) Harvey, E. Newton, McElroy, W.D., and Whiteley, A.H. "On Cavity Formation in Water". Jl. Applied Physics, vol. 18, no. 2, 1947, p. 162.

(5) Knapp, Robert T. "Cavitation Mechanics and its Relation to the Design of Hydraulic Equipment". James Clayton Lecture. Proc.(A) Institution of Mechanical Engineers, vol. 166, no. 2, 1952, p. 150-163.

(6) Parkin, Blaine R., and Holl, J.W. "Incipient-Cavitation Scaling Experiments for Hemispherical and 1.5 Caliber Ogive-Nosed Bodies". Joint study by the Hydrodynamics Laboratory, Calif. Inst. of Tech. and Ordnance Research Laboratory, Penn. State College, May 1953.

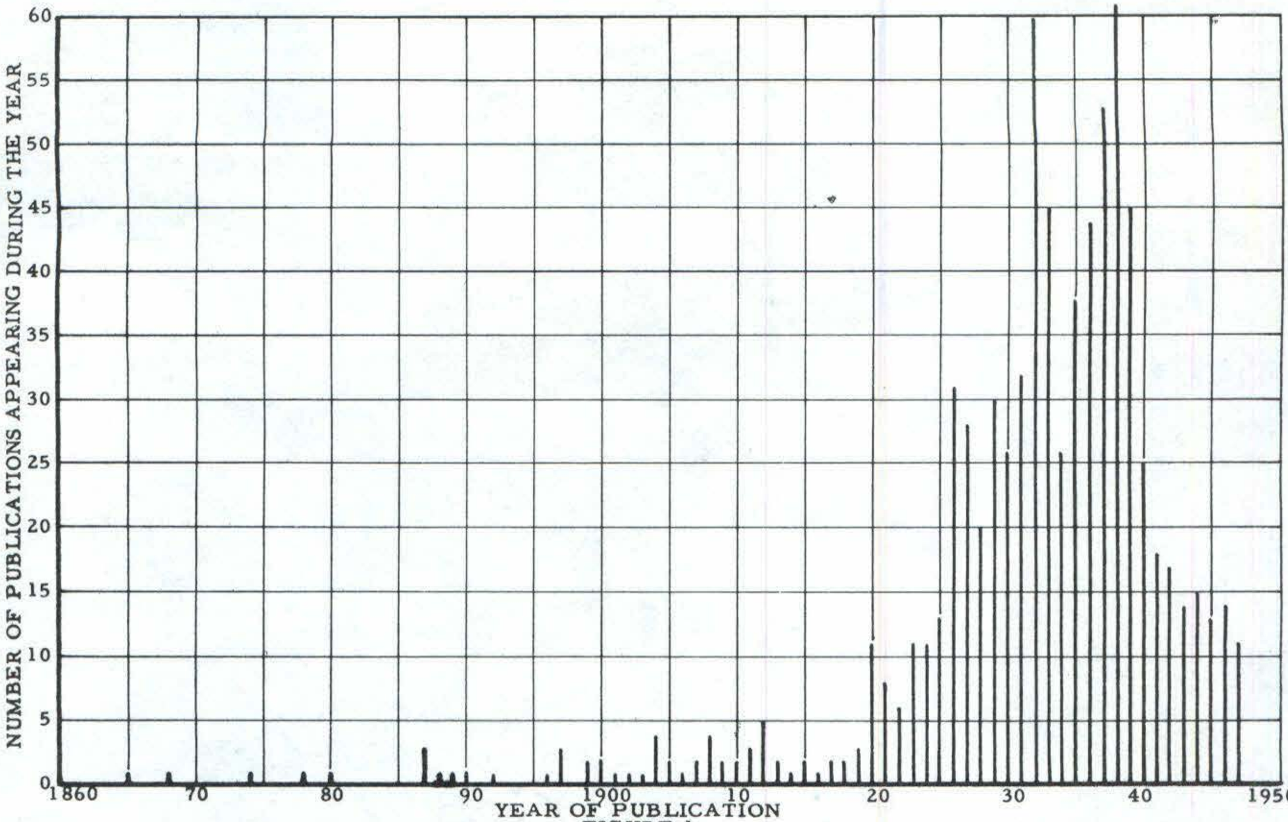

FIGURE 1
GROWTH OF CAVITATION LITERATURE

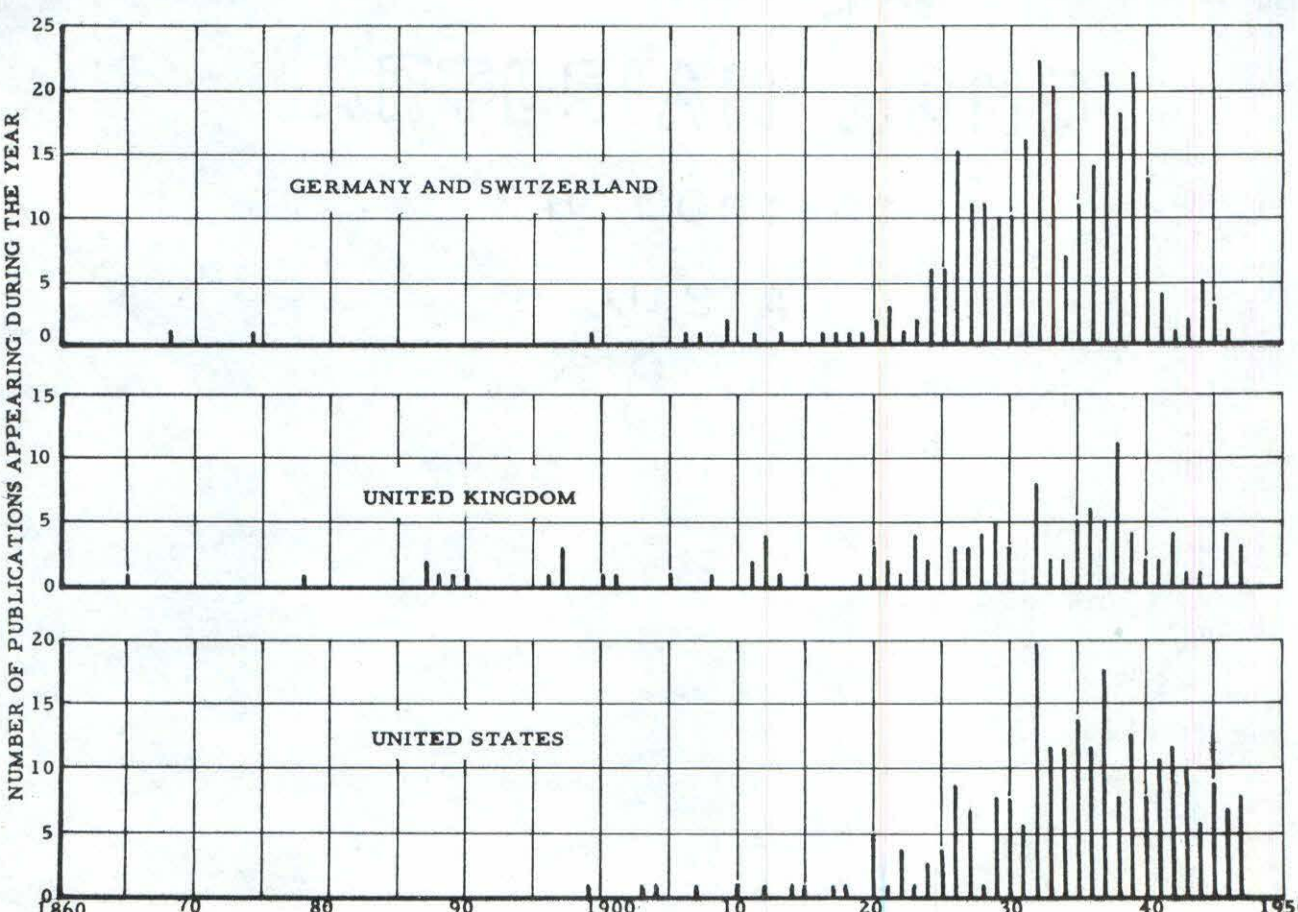

FIGURE 2
REGIONAL CONTRIBUTIONS TO CAVITATION LITERATURE